

ARMY RESEARCH LABORATORY

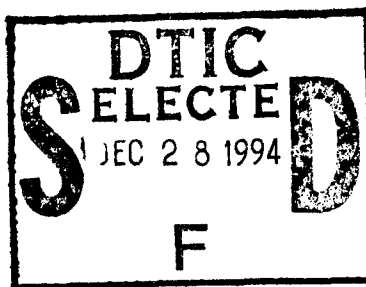


# A New Method of Evaluating The Explicit Magnetic-State-Dependent Energy In Semi-Emperical Calculations on Iron

Genrich L. Krasko

ARL-TR-650

November 1994



19941223 048

DATA QUALITY IMPROVED 1

Approved for public release; distribution unlimited.

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

# REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE November 1994	3. REPORT TYPE AND DATES COVERED Final July 1994	
4. TITLE AND SUBTITLE  A New Method of Evaluating the Explicit Magnetic-State-Dependent Energy in Semi-Empirical Calculations of Iron			5. FUNDING NUMBERS	
6. AUTHOR(S)  Genrich L. Krasko				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  Army Research Laboratory Watertown, MA 02172-0001 ATTN: AMSRL-MA-CC			8. PERFORMING ORGANIZATION REPORT NUMBER  ARL-TR-650	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION / AVAILABILITY STATEMENT  Approved for public release; distribution unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words)  The existing semi-empirical methods for use in atomic computer simulations in iron (such as various modifications of the Embedded Atom Method) have not explicitly taken account of the ferromagnetism per se. Rather, the adjustable parameters just have been fitted to mechanical and thermal properties of iron. However, when the magnetic properties are essential in affecting localized atomic behavior (e.g. in the vicinity of crystal defects), these methods may be inadequate. To remedy the situation, a procedure is suggested of explicitly calculating the magnetic contribution to the energy of individual atoms, as a function of their atomic environment. The method uses the Stoner approach, as previously developed in, and a data base obtained by the LMTO-Stoner calculations on BCC Fe under hydrostatic and tetragonal deformations, and Fe free surfaces. The procedure may be incorporated in any semi-empirical method: the ferromagnetic contributions to the bulk moduli, $C_{11}$ , $C_{12}$ and $C_{44}$ are easily calculated and may be subsequently used in adjusting the semi-empirical method parameters. Preliminary testing shows a good agreement with the magnetic properties obtained by the LMTO-Stoner calculations.				
14. SUBJECT TERMS  Ferromagnetism, Iron, Stoner Theory			15. NUMBER OF PAGES 17	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL	

## Introduction

During the recent decade, iron has been the object of extensive study by various first principles methods (for references and comparison of results for iron obtained by different methods see, e.g. [1-4]). However, the self-consistent spin-polarized calculations on BCC iron inevitably failed to predict the relative stability of the ferromagnetic (FM) BCC phase with respect to the nonmagnetic (NM) FCC (see discussion in [4]). This failure is believed to be mainly due to the local spin-density approximation used in the calculations.

Because of this fundamental difficulty, at the present time, an entirely *ab initio* analysis of structural phase transformations in iron is impossible. However calculations, which do not require comparison of energetics of different phases, like modeling of grain boundaries and free surfaces, can be successfully performed [5-7]. An alternative approach to the totally *ab initio* analysis is to introduce into the theory an adjustable parameter in order to make calculations more consistent with experimental observations.

Along this path, in Refs. [8-10], we have chosen to calculate the equilibrium magnetic moments as well as the magnetic contributions to the ground state energies of iron using the Stoner model of itinerant ferromagnetism [11], rather than performing spin-polarized calculations. The Stoner exchange parameter,  $I$ , can then serve as an adjustable parameter. Having made only one adjustment, such a procedure enabled us to perform the complete analysis of the relative stability of BCC and FCC phases, as well as the energetics of the BCC-FCC lattice deformation in iron.

In spite of the tremendous success in development, in the recent decade, of new first-principles methods of modeling, as well as efficient computer codes and proliferation of powerful high-speed computers, a totally first-principles modeling of important processes fundamentally affecting the mechanical properties of metallic alloys, is too computationally intensive and therefore practically impossible.

In response to the pressing necessity of filling this void, the efficient semi-empirical methods, such as different versions of the so-called Embedded Atom Method (EAM)[12], or Angular Force Method (AFM)[13], have been developed.

However, the existing semi-empirical methods for use in atomic computer simulations in iron still have not explicitly taken account of the ferromagnetism *per se*. Rather, the adjustable parameters just have been fitted to mechanical and thermal properties of iron. At the same time, when the magnetic properties are essential in affecting the atomic behavior (e.g. in the vicinity of crystal defects), these methods may be inadequate.

To remedy the situation, we suggest the procedure of explicitly calculating the magnetic contribution to the energy of individual atoms, as a function of their atomic environment. This procedure is based on the Stoner theory of itinerant ferromagnetism, and uses the information that has been accumulated in our earlier research on iron, mentioned above.

The plan of this paper is as follows. In Sec. 2 we discuss the Stoner model of itinerant ferromagnetism. In Sec. 3, we discuss the parametrization of the ingredient quantities to be used in semi-empirical calculations. Sec. 4 summarizes the procedure and discusses potential applications of the new method to EAM and AFM.

## **The Stoner Model of Itinerant Ferromagnetism**

The Stoner theory, first suggested in 1939 [11], has been successfully used in recent years in estimating both the equilibrium magnetization and magnetic energy of band electrons. This was made possible as a result of a rigorous formulation of the Stoner model as a perturbation approach in terms of microscopic electronic theory [14-17]. Particularly, the fundamental parameter of the theory, the Stoner exchange parameter,  $I$ , was understood in terms of density-functional characteristics. In iron, the theory explained the metamagnetic behavior of the FCC phase [14,18,7]. The Stoner approach in combination with self-consistent non-spin-polarized calculations enables one to perform the detailed analysis of ferromagnetic (FM) behavior, as well as identify all the possible magnetic stationary phases: both stable, metastable and even unstable, and find the areas of their emergence. Such an analysis, using traditional spin-polarized calculations is at present either too cumbersome and practically impossible.

The Stoner model in its original formulation postulates that the change of energy upon forming a FM state with moment  $\mathbf{m}$  consists of two parts. The first is the exchange energy contribution,  $-1/4 I \mathbf{m}^2$ , where the exchange parameter  $I$  is a constant. The second, the kinetic energy term is found by forming two subbands for spin up and down electrons by flipping  $\mathbf{m}/2$  spin down electrons

from just below the non-magnetic (NM) Fermi level into the unoccupied spin-up states just above the Fermi level. As was shown in [14-17], this procedure corresponds to the first order perturbation theory in  $\mathbf{m}/n_V$  ( $n_V$  is the number of valence electrons per atom). Thus, for a given  $\mathbf{m}$ , the magnetic contribution to the total energy is:

$$E_m = \frac{1}{2} \int_0^{\mathbf{m}} \mathbf{m}' / N(\mathbf{m}') d\mathbf{m}' - \frac{1}{4} I \mathbf{m}^2 \quad (1)$$

where  $N(\mathbf{m})$  is the NM density of states averaged between the Fermi levels of spins up and down electrons as found from the rigid subband shift. The procedure of 'constructing'  $N(\mathbf{m})$  is illustrated in Fig. 1.

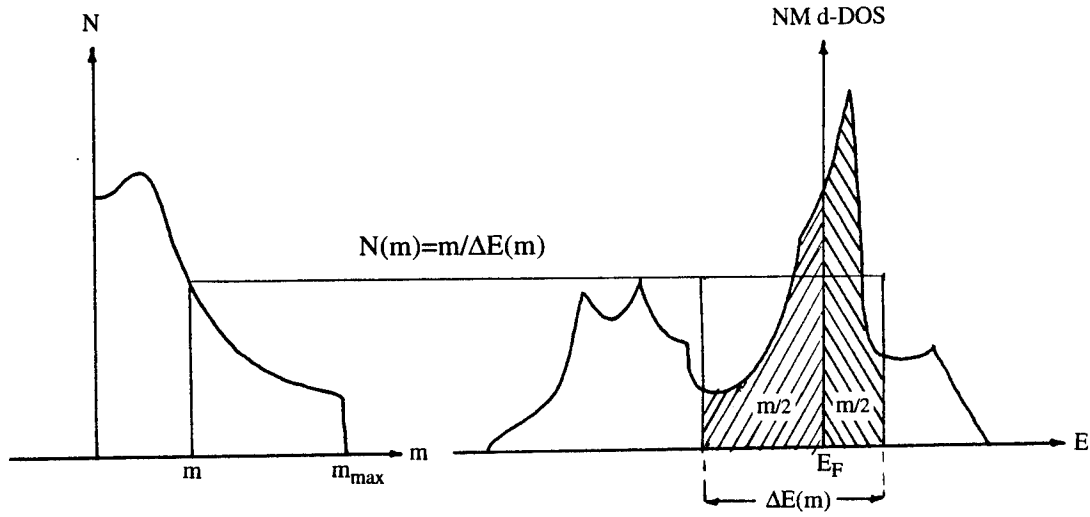


Fig. 1. Schematic construction of the  $N(\mathbf{m})$  function.

The stationary state requirement :

$$\partial E_m / \partial \mathbf{m} = 0,$$

gives, apart from the "trivial" solution,  $\mathbf{m}=0$ , the criterion for arising a FM state:

$$I \cdot N(\mathbf{m}) = 1 \quad (2)$$

Suppose Eq. (2) has a solution,  $\mathbf{m}$ . Then the corresponding FM state is stable ( $\partial^2 E_m / \partial \mathbf{m}^2 > 0$ ) if

$$\partial N(\mathbf{m}) / \partial \mathbf{m} < 0 \quad (3)$$

otherwise it is unstable ( $\partial^2 E_m / \partial \mathbf{m}^2 < 0$ ). However, even if Eqs. (2,3) hold, the FM state may not occur if  $E_m > 0$ . In this case the FM state is metastable.

As for the NM state,  $\mathbf{m}=0$ , it is stable and may coexist with a FM state (metamagnetic situation), only so far as

$$[ \partial^2 E_m / \partial \mathbf{m}^2 ]_{\mathbf{m}=0} > 0 \quad (4)$$

or, equivalently,

$$I N(E_F) < 1 \quad (5)$$

where  $N(E_F)$  is the NM density of states (DOS) at the Fermi level ( $N(E_F)=N(0)$ ).

From the perturbation theory analysis [14-17],  $I$  can be found in terms of the NM system. From the linear response theory [17] it follows:

$$I = \int d^3r \gamma^2(r) |K(r)| \quad (6)$$

(the three-dimensional integral is taken over the whole volume of crystal) where

$$\gamma(r) = \frac{\sum_i^{\text{occ}} \delta(E_F - E_i) |\psi_i(r)|^2}{N(E_F)}$$

and

$$K(r) = 1/2 [ d^2 E_{xc}(r, \mathbf{m}) / d\mathbf{m}^2 ]_{\mathbf{m}=0}$$

Here  $E_i$ ,  $\psi_i(r)$  are respectively the eigenvalues and the wave functions of the NM system;  $E_{xc}(r, \mathbf{m})$  is the exchange-correlation functional.

An important property of the averaged DOS  $N(\mathbf{m})$  is that, being multiplied by the d-electron "band width",  $W$ , it happens to be virtually independent of volume, or the Wigner-Seitz (WS) radius,  $s$ . Then Eq. (2) reads:

$$N(\mathbf{m}) = W(s)/I(s) \quad (7)$$

Where  $N(\mathbf{m}) = W * N(\mathbf{m})$ . Fig. 2 shows  $N(\mathbf{m})$  curves for two  $s$  values. The right-hand side of the above Eq. does depend on  $s$ , and this dependence is important.

Until recently, the Stoner parameter,  $I$ , has been believed to be essentially a constant, independent of both the volume and the crystal structure of the metal. Our calculations on both the BCC and FCC iron [8-10] revealed the monotonic,

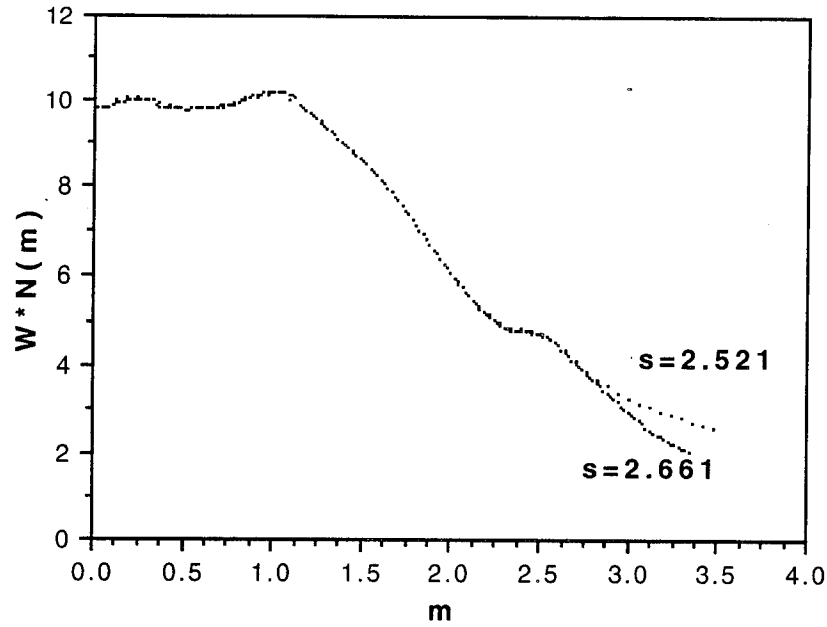


Fig. 2.  $N(\mathbf{m})$ s for BCC lattice for two WS radii.

though rather weak, dependence of  $I$  on the WS radius,  $s$ . Both the magnetic energy, Eq.(1), the equilibrium magnetic moment,  $\mathbf{m}$ , (as found from Eq. (2)), and the equilibrium atomic volume, happen to be rather sensitive to the values of  $I$ . The idea of papers [8-10] was to adjust the value of  $I$ , so that the equilibrium WS radius,  $s_0$ , for the FM BCC phase be equal to the experimental value. In Table I we compare the calculated  $s_0$ , for  $I = \beta I_0$  [ where  $I_0$  is the "ab initio" value, Eq. (6), and  $\beta = 1.000, 1.025, 1.050, 1.075$  and  $1.090$ ]. One can see that for  $\beta = 1.075$ , the equilibrium WS radius,  $s_0 = 2.659$  a.u., almost matches the experimental value. Therefore, we have chosen  $\beta = 1.075$  as the "universal" enhancement factor; all the calculations in [9] for the whole range of  $c/a$  values were done with this  $\beta$ . No other adjustments of any parameters were performed.

Table 1.  
Dependence of the equilibrium WS radius for the FM BCC phase on the Stoner parameter enhancement factor,  $\beta$ .

$\beta$	1.000	1.025	1.050	1.075	1.090
$s$ , a.u. <sup>a</sup>	2.648	2.650	2.654	2.659	2.664

a) Experimental value,  $s = 2.661$  a.u. (Ref. [19])



We used the LMTO method [20] with the so-called combined correction term [20], and the Madelung electrostatic correction [21]. Scalar relativistic calculations on uniform meshes of 1540 points in the irreducible wedges of BCT Brillouin zones were done, with the exchange-correlation functional of von Barth and Hedin [22]. Also, the frozen core approximation was used [23].

Our calculations were done for 12  $c/a$  -values :  $1.0 \leq c/a \leq \sqrt{2}$ . For each  $c/a$ , self-consistent non-spin-polarized calculations were performed for 9 values

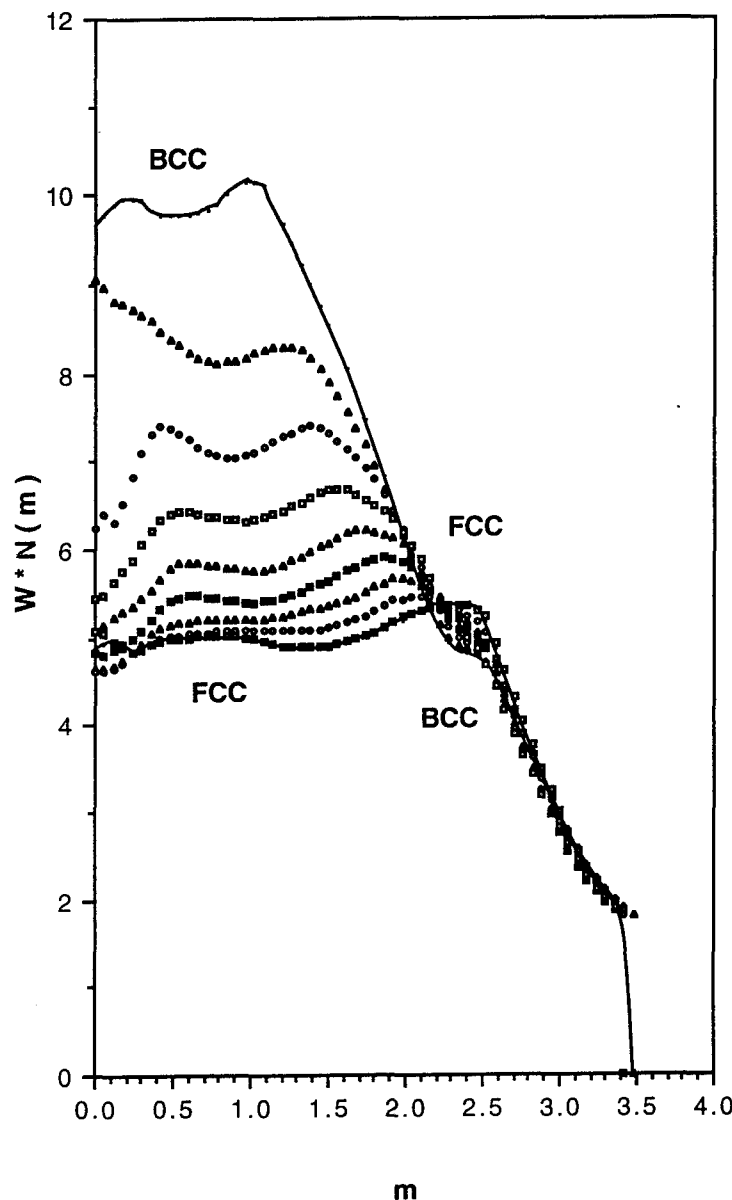


Fig. 3. The  $N(\mathbf{m})$  functions for FCT lattices. Solid lines are the BCC and FCC curves. The other curves correspond to the intermediate  $c/a$  values.

of the WS radius,  $s$  ( $2.521 \text{ a.u.} \leq s \leq 2.788 \text{ a.u.}$ ). In each calculation, after convergence had been achieved, the Stoner parameters,  $I_0(c/a, s)$ , Eq.(6), and then  $I = 1.075I_0$  were found and the averaged DOS,  $N(\mathbf{m})$  was generated. Then the Stoner equation, Eq.(2), was solved for the equilibrium magnetic moment,  $\mathbf{m}$ , and the magnetic energy  $E_m$ . The data base generated in this series of calculations will be used in our new method. Fig. 3 shows the  $N(\mathbf{m})$  curves for BCT lattice.

The above data, however, reflect only the tetragonal deformation. An important ingredient of the new method, which is to be used in modeling GBs and free surfaces, should be information on free surfaces.

The necessary data were provided by Dr. R. Wu of Northwestern University, whose work in Prof. Art Freeman's group, has been a part of the SRG effort.

In the next section we

will describe in detail the parametrization of the data and discuss the algorithm of the method.

### **Parametrization of the First-Principles Data and the Method Algorithm.**

Using the Stoner model with the adjusted exchange parameter, we have calculated the structural properties of BCC and FCC iron and, for the first time, the energetics of the intermediate states along the Bain deformation path .

Any semi-empirical method has to be able to somehow describe the environment of the atom of interest. It is known from a vast experience of tight-binding calculations (see, e.g.[24]), that the number of neighbors is an important parameter which plays a crucial role in band-structure calculations. We have chosen, therefore, to introduce the so-called "effective number of neighbors",  $Z_{\text{eff}}$ , to allow for the atomic environment. Since all the quantities are to be parametrized in terms of  $Z_{\text{eff}}$ , its definition is not very critical. It is important, however, that  $Z_{\text{eff}}$  should reflect the real atomic environment. We define

$$Z_{\text{eff}} = \sum (R_{\text{min}}/R)^5 \exp(1-(R/R_{\text{min}})^2) \quad (8)$$

where the summation is over atom coordinates  $R$  ( $R_{\text{min}}$  is the distance from a given atom to its nearest neighbor). No cut-off radius is introduced, but, in fact, the exponential provides a rather fast sum convergence. Fig. 4 shows the dependence of  $Z_{\text{eff}}$  on  $c/a$  in body-centered tetragonal (BCT) lattices. One can see, that  $Z_{\text{eff}}$  for BCC and FCC equal respectively to 10.37 and 12.63, while the corresponding nearest neighbor numbers are 8 and 12. The 10.37 number actually reflects the fact that the 6 second nearest neighbors in the BCC lattice are also situated rather close to the first nearest neighbors ( $R_{2\text{nd}}/R_{1\text{st}}=1.155$ ); in the FCC lattice they are farther away ( $R_{2\text{nd}}/R_{1\text{st}}=1.414$ ). Therefore the 6 second nearest neighbors in the FCC lattice are less important giving a smaller contribution to  $Z_{\text{eff}}$ .

Apart from the "environment" or "structure" parameter,  $Z_{\text{eff}}$ , an important parameter is the volume per atom. In a perfect lattice the atomic volume, or, equivalently, the WS sphere of radius,  $s$ , can be easily found. In a deformed crystal, or a crystal with defects, the atomic volume is difficult to define, and, in fact it is a "bad" parameter.

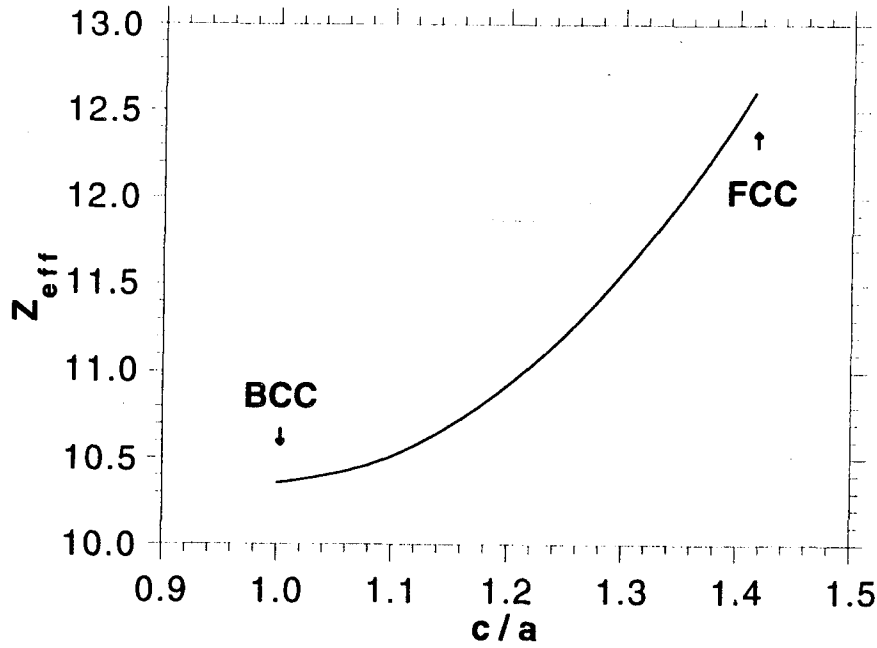


Fig. 4.  $Z_{\text{eff}}$  ( $c/a$ ) for BCT lattice.

As was mentioned above, the left-hand side of Eq. (7),  $N(\mathbf{m})$ , virtually does not depend on  $s$ . However, the right-hand side does depend on  $s$ , where this dependence is mostly due to the d-electron band width,  $W$ .

It is known (see, e.g., [24]), that in perfect crystals  $W \sim 1/s^5$ . Therefore, it is convenient to parametrize  $W$  in the form:

$$W = A(Z_{\text{eff}}) (\sum 1/R^{10})^{1/2} \quad (9)$$

As a result,  $W$  has the right volume dependence.

The values of  $W$  are found as a by-product of first-principles calculations: our data base contains the values for a number of BCT lattices, as well as the BCC (111) free surface. Fig. 5 shows the results of fitting the function, Eq.(2) to the calculated  $W$ 's. The function  $A(Z_{\text{eff}})$  is approximated by a polynomial in the interval  $5.2 \leq Z_{\text{eff}} \leq 12.61$  (note the  $Z_{\text{eff}}$  values between 5.2 and 10.354 correspond to the (111) free surface).

We assume that the Stoner parameter,  $I$ , is only weakly volume dependent. However, it does depend on atomic environment, i.e. on  $Z_{\text{eff}}$ . We approximated the values of  $I$ , Eq. (6) (as found from the first-principles calculations, and augmented by factor 1.075; see section 2) by two polynomials in  $Z_{\text{eff}}$  (Fig.6).

Thus, if  $N(\mathbf{m})$  is known, then, for a given  $Z_{\text{eff}}$  and  $W$ , the equation Eq. (7) can be solved for the magnetic moment,  $\mathbf{m}=\mathbf{m}(W/I)$ . The next step is calculating  $E_{\text{kin}}$ , the kinetic energy contribution (the integral in Eq. (1)), and then the total ferromagnetic energy,  $E_{\text{m}}$ .

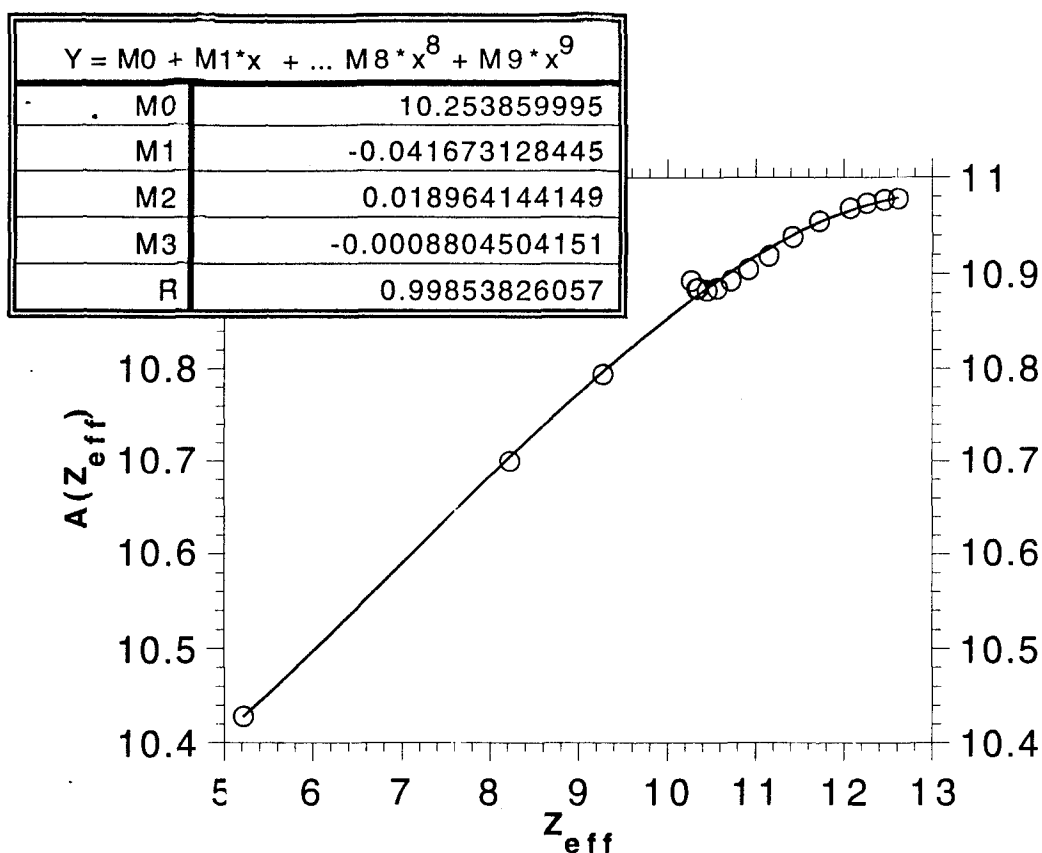


Fig. 5. Factor  $A(Z_{eff})$  as a polynomial of  $Z_{eff}$ .

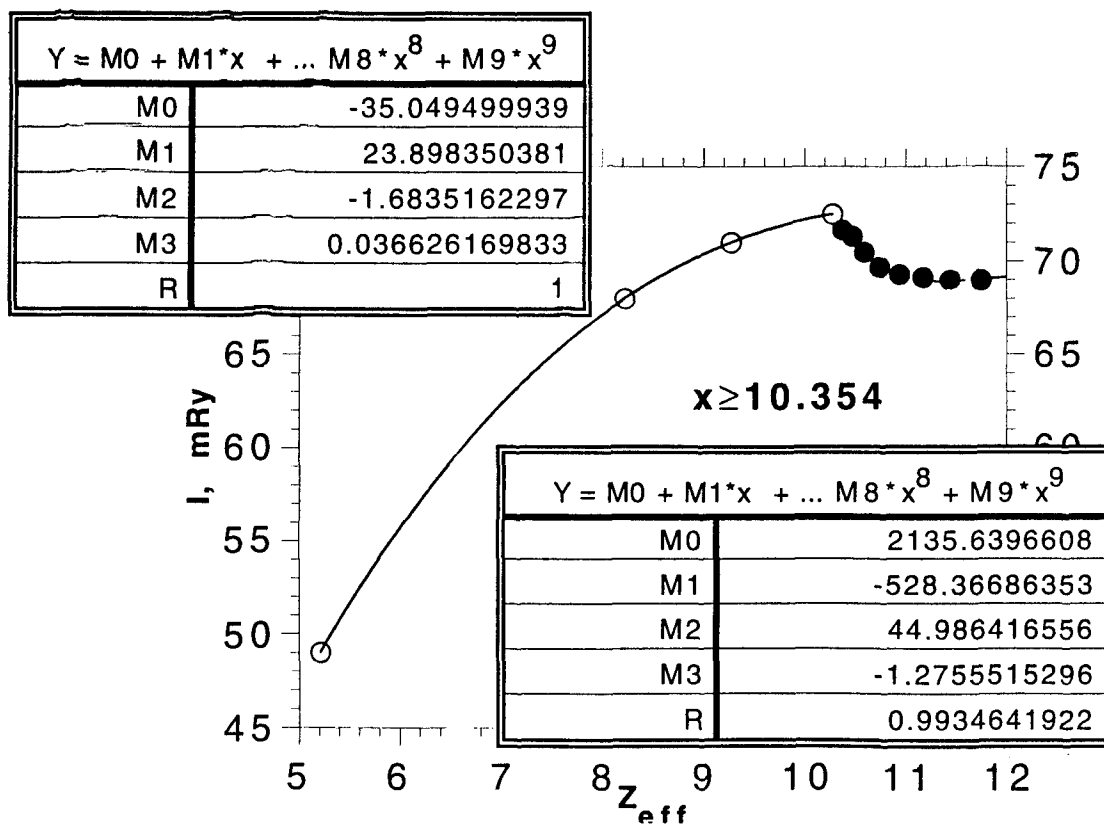


Fig. 6. The Stoner parameter,  $I$ , as approximated by two polynomials in  $Z_{eff}$

Both the  $N(\mathbf{m})$ ,  $\mathbf{m}(x)$ ,  $x=W/I$ , and  $E_{\text{kin}}(\mathbf{m})$  can be directly introduced into the computer code as DATA statements. The three data sets are the two-dimensional arrays,  $Z_{\text{eff}}$  being the second variable. It is known, that ferromagnetism is unstable beyond a definite range of atomic volume/structure values. This translates into a definite restriction for the values of  $x=W/I$ . The maximal allowable value of  $x$  as a function of  $Z_{\text{eff}}$  is shown in Fig.7.

Following the above prescription, the computer code was developed, in the form of subroutine STONER(ni, ri, amag, emag).

The procedure of calculations is as follows. The subroutine STONER is called from a main program which generates ni and ri, the total number of neighboring atoms and their distances from the atom of interest (ni should include as many atoms as it may be necessary for the  $Z_{\text{eff}}$  to converge), and amag and emag are the output magnetic moment on the atom of interest and its ferromagnetic energy.

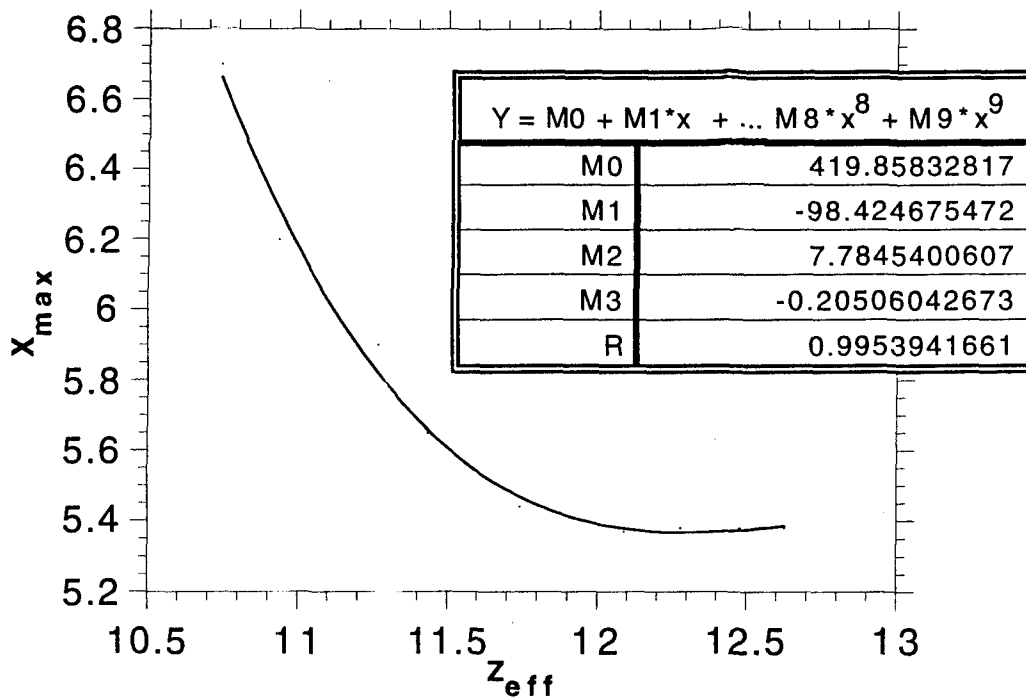


Fig. 7. The maximal value of parameter  $x=W/I$ , at which the ferromagnetic solution becomes unstable, as a function of  $Z_{\text{eff}}$ .

In the subroutine, first the  $Z_{\text{eff}}$  and  $W$  (using function  $\text{fac}(z)$  which stands for  $A(Z_{\text{eff}})$ ) are calculated, then the Stoner parameter  $I(Z_{\text{eff}})$  and  $W/I$  are found for a given  $Z_{\text{eff}}$ . The next step is solving Eq. (7) for the magnetic moment  $\mathbf{m}$  -- simply reading the value from the corresponding array using two-dimensional interpolation. After finding  $\mathbf{m}$ , the kinetic energy,  $E_{\text{kin}}(\mathbf{m}, Z_{\text{eff}})$ , is found again

by two-dimensional interpolation (the interpolation subroutine is included in the code). Fig. 8 shows the  $E_{\text{kin}}/W$  plots for BCC,  $c/a=1.24$  and FCC. The last step is calculation of the ferromagnetic energy:

$$E_m = E_{\text{kin}} - 1/4 I m^2 \quad (10)$$

Wherever Eq. (7) does not have a ferromagnetic solution (the ferromagnetic solution is unstable), or  $E_m$  is positive (the ferromagnetic solution is metastable), the subroutine returns the values  $m=0.$ , and  $E_m=0$ .

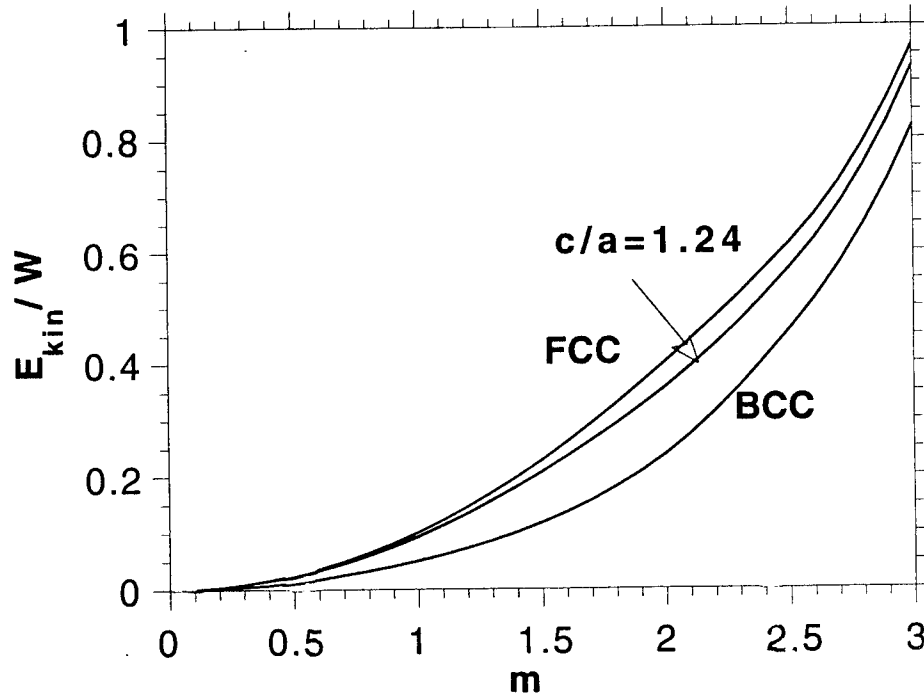


Fig. 8. The  $E_{\text{kin}}/W$  plots for BCC,  $c/a=1.24$  and FCC

The test runs of the subroutine for BCT lattices for  $s=2.661$  (equilibrium volume for BCC Fe) from  $c/a=1.0$  (BCC) through  $c/a=1.32$  (at higher  $c/a$  at this volume the ferromagnetic state is unstable) showed an excellent agreement between the values of  $m$  and  $E_m$  calculated by the new method and the results of the LMTO calculations (the only exception is  $c/a=1.32$ , where the energy is already quite small). Table 2 compares these results.

Table 2  
Comparison of values of  $\mathbf{m}$  and  $E_m$  as calculated by the new procedure and by the  
LMTO first-principles method

c/a	$\mathbf{m}^{\text{calc}}$ ( $\mu_B$ )	$\mathbf{m}^{\text{LMTO}}$	$E_m^{\text{calc}}$ (mRy)	$E_m^{\text{LMTO}}$
1.00	2.235	2.223	-30.39	-30.14
1.08	2.251	2.253	-25.34	-25.46
1.12	2.273	2.266	-20.93	-20.84
1.16	2.299	2.291	-15.79	-15.53
1.20	2.274	2.264	-10.35	-10.19
1.24	2.309	2.335	-5.987	-6.103
1.28	2.370	2.365	-2.924	-2.938
1.32	2.446	2.433	-0.277	-0.095

### Potential Applications of the New Method in AFM and EAM

The new procedure can be easily adopted by any semi-empirical method. The most popular method, the EAM, in its various modifications, fits some of the calculated quantities to their experimental values. In all EAM versions, among those quantities are the bulk modulus and the three elastic moduli:  $C_{11}$ ,  $C_{12}$  and  $C_{44}$ .

In order to implement the new procedure, a series of calculations for hydrostatic, tetragonal and monoclinic (or triclinic) deformations of BCC Fe have to be performed, and the ferromagnetic contributions to the corresponding elastic moduli found. Then, this information is to be used in fitting the adjustable parameters in the corresponding EAM.

Originally, it was planned to implement the new procedure to the recently developed AFM. The validity and advantages of the AFM were then to be tested on the ferromagnetic Iron. However, the results of our recent calculations [25], using the AFM for modeling the relaxation of a grain boundary in tungsten, appear to be somewhat doubtful.

Our previous investigation using the so-called Finnis-Sinclair modification of the EAM [6] for GB relaxation in tungsten, discovered an anomalous relaxation of the third (from the GB plane) plane of W atoms, the so-called " $\omega$ -phase effect". It was also observed in Fe by the EAM simulation [26], our Finnis-

Sinclair calculations [27], and restricted relaxation calculations using the first-principles method [7]. However, this effect, which is easily understood from the physical point of view [6], was not obtained in the AFM GB relaxation in W. This negative result has suggested that the detailed analysis of the AFM should be put on hold. Instead, the emphasis should be given to the implementation of our new procedure to a more traditional version of EAM, recently developed by the author. This project will be carried out shortly.

## ACKNOWLEDGEMENTS

The author is grateful to Dr. R. Wu for providing his unpublished results of the electronic densities of states for (111) free surface in Fe. The author is also grateful to Dr. R.P.I. Adler and Dr. M. Azrin for their interest and invaluable support. Valuable discussions with Dr. R. J. Harrison are also gratefully acknowledged. The LMTO code used for first-principles calculations was developed by Prof. N. Christensen.

## REFERENCES

1. V. L. Moruzzi, J. F. Janak and A. R. Williams. *Calculated Electronic Properties of Metals*, Pergamon Press, New York, 1978
2. K. B. Hathaway, H. J. F. Jansen and A. J. Freeman, Phys. Rev. B 31, 7603 (1985)
3. V. L. Moruzzi, Phys. Rev. Lett. 57, 2211 (1986); V. L. Moruzzi, P. M. Marcus, K. Schwarz, and P. Mohn, Phys. Rev. B 34, 1784 (1986)
4. H. J. F. Jansen and S. S. Peng. Phys. Rev. B 37, 2689 (1988)
5. G. L. Krasko and G. B. Olson, Solid State Commun. 76, 247 (1990); G. L. Krasko and G. B. Olson, Solid State Commun. 79, 113 (1991)
6. G. L. Krasko, Int. J. Refractory Metals and Hard Materials (in press)
7. R. Wu and A. J. Freeman, J. Mater. Res. 7, 2403 (1992); R. Wu, A. J. Freeman, and G. B. Olson, Phys. Rev. B 47, 6855 (1993); R. Wu and A. J. Freeman, Phys. Rev. B 47, 3904, 14932 (1993)
8. G. L. Krasko, Phys. Rev. B 36, 8565 (1987)
9. G. L. Krasko, Solid State Communications, 70, 1099 (1989)
10. G. L. Krasko and G. B. Olson, Phys. Rev. B 40, 11536 (1989); G. L. Krasko and G. B. Olson, J. Appl. Phys. 67, 4570 (1990)
11. E. C. Stoner, Proc. R. Soc. London, Ser. A 169, 339 (1939)



12. M. W. Finnis and J. E. Sinclair, *Phil. Mag.*, A50,45 (1984) ; errata , *ibid*, A53 , 161 (1986); M. S. Dow and M. I. Baskes, *Phys. Rev. B*, 29, 6443 (1984); M. S. Dow, *ibid*, 39, 7411 (1989), and references therein.
13. A. E. Carlsson, in *Solid State Physics*, vol 44, 1(1990); A. E. Carlsson, *Phys. Rev. B*44, 6590 (1991); A. E. Carlsson and J. Zou, in *Materials Theory and Modeling*, ed. J. Broughton, P. Bristow, and J. Newsam, Mat. Res. Soc. Symp. Proc, vol 291, 183 (1993); J. Zou and A. E. Carlsson, *Phys. Rev. B*47, 2961 (1993)
14. O. K. Andersen, J. Madsen, U. K. Paulsen, O. Jepsen, and J. Kollar, *Physica*, B 86-88, 249 (1977)
15. S. H. Vosko and P. Perdew, *Can. J. Phys.* 53, 1385 (1975)
16. O. Gunnarsson, *J. Phys. F*6, 587 (1976)
17. J. F. Janak, *Phys. Rev. B* 16, 255 (1977)
18. U. K. Poulsen, J. Kollar, and O. K. Andersen, *J. Phys. F* 6, L241 (1976); D. M. Roy and D. G. Pettifor, *J. Phys. F* 7, 1183 (1977)
19. W. P. Pearson, *Handbook of Lattice Spacings and Structures of Metals and Alloys*, Pergamon Press, Oxford, 1964
20. O. K. Andersen, O. Jepsen, and D. Gloetzel in *Highlights of Condensed Matter Theory*, edited by F. Bassani, F. Fumi, and M. P. Tosi (North Holland, New York, 1985); O. K. Andersen in *Electronic Structure of Complex Systems*, edited by P. Phariseau and W.M.Timmerman (Plenum, New York, 1984) p. 11-65 ; H. L. Skriver, *The LMTO Method* (Springer, Berlin, 1984)
21. D. Gloetzel and O. K. Andersen (unpublished) ; N. E. Christensen, *Phys. Rev. B* 32, 207 (1985); H. L. Skriver , *Phys. Rev. B* 31 , 1909 (1985)
22. U. von Barth and L. Hedin, *J. Phys. C* 5, 1629 (1972)
23. U. von Barth and C. D. Gelatt, Jr., *Phys. Rev. B* 21, 2222 (1980)
24. D. G. Pettifor, in *Physical Metallurgy*, Ed. R. W. Cahn and P. Hansen, North Holland, 1983, Part I, p. 73
25. R. J. Harrison and G. L. Krasko, unpublished results
26. R. J. Harrison, F. Spaepen, A. F. Voter, and S.-P. Chen, in *Innovations in Ultrahigh-Strength Steel Technology*, Sagamore Army Materials Research Conference Proc., vol 34, ed. G.B. Olson, M. Azrin and E. S. Wright, 1987, p. 651-692
27. G. L. Krasko, in *Structure and Properties of Interfaces* MRS Symp. Proc.,238, Pittsburgh, PA, p.481 (1992).

# DISTRIBUTION LIST

No. of Copies	To
1	Office of the Under Secretary of Defense for Research and Engineering, The Pentagon, Washington, DC 20301
	Director, U.S. Army Research Laboratory, 2800 Powder Mill Road, Adelphi, MD 20783-1197
1	ATTN: AMSRL-OP-SD-TP, Technical Publishing Branch
1	AMSRL-OP-SD-TA, Records Management
1	AMSRL-OP-SD-TL, Technical Library
	Commander, Defense Technical Information Center, Cameron Station, Building 5, 5010 Duke Street, Alexandria, VA 23304-6145
2	ATTN: DTIC-FDAC
1	MIA/CINDAS, Purdue University, 2595 Yeager Road, West Lafayette, IN 47905
	Commander, Army Research Office, P.O. Box 12211, Research Triangle Park, NC 27709-2211
1	ATTN: Information Processing Office
	Commander, U.S. Army Materiel Command, 5001 Eisenhower Avenue, Alexandria, VA 22333
1	ATTN: AMCSCI
	Commander, U.S. Army Materiel Systems Analysis Activity, Aberdeen Proving Ground, MD 21005
1	ATTN: AMXSY-MP, H. Cohen
	Commander, U.S. Army Missile Command, Redstone Arsenal, AL 35809
1	ATTN: AMSMI-RD-CS-R/Doc
	Commander, U.S. Army Armament, Munitions and Chemical Command, Dover, NJ 07801
1	ATTN: Technical Library
	Commander, U.S. Army Natick Research, Development and Engineering Center Natick, MA 01760-5010
1	ATTN: SATNC-MI, Technical Library
	Commander, U.S. Army Satellite Communications Agency, Fort Monmouth, NJ 07703
1	ATTN: Technical Document Center
	Commander, U.S. Army Tank-Automotive Command, Warren, MI 48397-5000
1	ATTN: AMSTA-ZSK
1	AMSTA-TSL, Technical Library
	President, Airborne, Electronics and Special Warfare Board, Fort Bragg, NC 28307
1	ATTN: Library
	Director, U.S. Army Research Laboratory, Weapons Technology, Aberdeen Proving Ground, MD 21005-5066
1	ATTN: AMSRL-WT
2	Technical Library

No. of Copies	To
1	Commander, Dugway Proving Ground, UT 84022 ATTN: Technical Library, Technical Information Division
1	Commander, U.S. Army Research Laboratory, 2800 Powder Mill Road, Adelphi, MD 20783 ATTN: AMSRL-SS
1	Director, Benet Weapons Laboratory, LCWSL, USA AMCCOM, Watervliet, NY 12189 ATTN: AMSMC-LCB-TL
1	AMSMC-LCB-R
1	AMSMC-LCB-RM
1	AMSMC-LCB-RP
3	Commander, U.S. Army Foreign Science and Technology Center, 220 7th Street, N.E., Charlottesville, VA 22901-5396 ATTN: AIFRTC, Applied Technologies Branch, Gerald Schlesinger
1	Commander, U.S. Army Aeromedical Research Unit, P.O. Box 577, Fort Rucker, AL 36360 ATTN: Technical Library
1	U.S. Army Aviation Training Library, Fort Rucker, AL 36360 ATTN: Building 5906-5907
1	Commander, U.S. Army Agency for Aviation Safety, Fort Rucker, AL 3636 ATTN: Technical Library
1	Commander, Clarke Engineer School Library, 3202 Nebraska Ave., N., Fort Leonard Wood, MO 65473-5000 ATTN: Library
1	Commander, U.S. Army Engineer Waterways Experiment Station, P.O. Box 631, Vicksburg, MS 39180 ATTN: Research Center Library
1	Commandant, U.S. Army Quartermaster School, Fort Lee, VA 23801 ATTN: Quartermaster School Library
1	Naval Research Laboratory, Washington, DC 20375 ATTN: Code 6384
1	Chief of Naval Research, Arlington, VA 22217 ATTN: Code 471
1	Commander, U.S. Air Force Wright Research and Development Center, Wright-Patterson Air Force Base, OH 45433-6523 ATTN: WRDC/MLLP, M. Forney, Jr.
1	WRDC/MLBC, Mr. Stanley Schulman
1	U.S. Department of Commerce, National Institute of Standards and Technology, Gaithersburg, MD 20899 ATTN: Stephen M Hsu, Chief, Ceramics Division, Institute for Materials Science and Engineering

No. of Copies	To
1	Committee on Marine Structures, Marine Board, National Research Council, 2101 Constitution Avenue, N.W., Washington, DC 20418
1	Materials Sciences Corporation, Suite 250, 500 Office Center Drive, Fort Washington, PA 19034
1	Charles Stark Draper Laboratory, 555 Technology Square, Cambridge, MA 02139
1	General Dynamics, Convair Aerospace Division, P.O. Box 748, Fort Worth, TX 76101
1	ATTN: Mfg. Engineering Technical Library
	Plastics Technical Evaluation Center, PLASTEC, ARDEC, Bldg. 355N, Picatinny Arsenal, NJ 07806-5000
1	ATTN: Harry Pebly
1	Department of the Army, Aerostructures Directorate, MS-266, U.S. Army Aviation R&T Activity - AVSCOM, Langley Research Center, Hampton, VA 23665-5225
1	NASA - Langley Research Center, Hampton, VA 23665-5255
	U.S. Army Vehicle Propulsion Directorate, NASA Lewis Research Center, 2100 Brookpark Road, Cleveland, OH 44135-3191
1	ATTN: AMSRL-VP
	Director, Defense Intelligence Agency, Washington, DC 20340-6053
1	ATTN: ODT-5A, Mr. Frank Jaeger
	U.S. Army Communications and Electronics Command, Fort Monmouth, NJ 07703
1	ATTN: Technical Library
	U.S. Army Research Laboratory, Electronic Power Sources Directorate, Fort Monmouth, NJ 07703
1	ATTN: Technical Library
	Director, U.S. Army Research Laboratory, Watertown, MA 02172-0001
2	ATTN: AMSRL-OP-WT-IS, Technical Library
5	Author